SCIENCE FOR GLASS PRODUCTION

UDC 666.1.038.3:681.3.06

A CALCULATION ALGORITHM FOR NONLINEAR THERMAL TREATMENT OF SHEET GLASS

A. I. Shutov,[1] A. S. Ostapko,[1] T. S. Ostapko,[1] and K. A. Medvedev[1]

Translated from Steklo i Keramika, No. 1, pp. 6 – 8, January, 2003.

It is demonstrated that using the Fridkin and Gardon – Narayanaswami algorithms makes it possible to describe conditions of glass hardening with a sufficient accuracy and provides enough reason to calculate nonlinear glass treatment regimes, which makes it possible to predict new consumer properties in sheet glass.

One of the most important operations in thermal treatment of sheet glass is hardening. Articles treated in this way have high strength parameters and a safe type of destruction. However, they cannot undergo machine treatment (cutting, drilling, grinding, etc.) due to their self-sustaining destruction. It is essential to develop such method for thermal treatment of glass that would yield a product combining the possibility of mechanical treatment with a high level of strength.

The only solution so far found for this problem is complex thermal treatment (CTT) of sheet glass [1]. This method, similarly to traditional hardening, can be implementation both on horizontal and on vertical hardening lines with a minimum correction required of the technological process. The only problem encountered by production engineers is the absence of algorithms for estimating the properties of sheet glass after CTT.

The method for calculating the process of hardening under a constant intensity of heat exchange with the coolant (α = const) is sufficiently well investigated [2].

At the same time, implementation of nonlinear heat treatment conditions with a variable heat transfer coefficient in cooling ($\alpha \neq$ const) would make it possible to significantly expand the range of consumer properties of sheet glass, which would open additional prospects in producing laminated protective glass with a significantly decreased weight of articles while preserving the safety parameters. Furthermore, it has been established in preliminary studies that the CTT process is going to be less energy-consuming than classical hardening.

The proposed algorithm is based on the studies [1] making it possible to calculate temporary and residual stresses taking into account the nonlinear heat transfer coefficient α throughout the entire thermal treatment.

The difficulties in the development of a method for calculating stresses in CTT technology are related to the impossibility of using the classical Fourier solutions for the heat transfer coefficient that is nonlinear in time. Using the Fourier method [3] in these conditions. a researcher is confronted with objective inadequacy of the obtained solutions.

Let us consider cooling of glass for a time period $\tau_1 = 20$ sec with an air flow α_1 and subsequent exposure of glass under free convection in the context of a qualitative estimate (Fig. 1). During intense cooling the temperatures of the outer and inner layers (curves *1* and *2*) correlate with the true temperature field. However, if the Fourier equations are used when the cooling regime changes (points *A* and *B*), the temperature of the outer layer "freezes" (curve *3*) and the outer layer temperature abruptly drops (curve *4*), which contradicts common sense.

In this case balance equations are preferable. An example of such equations was used by R. Z. Fridkin and

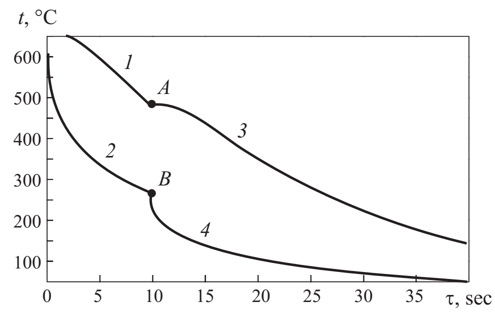

Fig. 1. Temperature fields in the course of complex thermal treatment (calculated by the Fourier method).

[1] Belgorod State Technological Academy of Construction Materials, Belgorod, Russia.

0361-7610/03/0102-0007$25.00

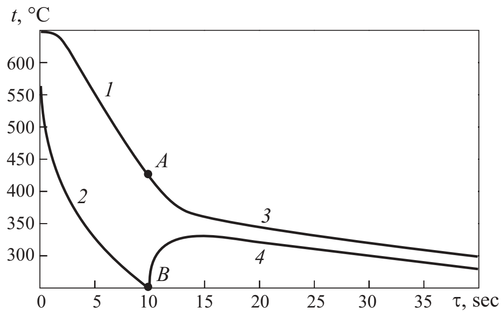

Fig. 2. Temperature fields in the course of complex thermal treatment (calculated by the Fridkin method).

O. V. Mazurin [4] in calculating heating of glass. That algorithm implies the calculation not only of the conductive component of heat transfer but of the radiant component as well, since at low cooling intensity the latter constitutes up to 30% [5]. The distinctive feature of the algorithm described in the present paper is calculation of the integral radiation component using the Stefan – Boltzmann formula (without using power series), which makes it less cumbersome.

The qualitative representation (Fig. 2) of variation of the temperatures of the inner (curves *1* and *3*) and outer (curves *2* and *4*) layers yields a more sensible result in the form of a temporary "outburst" of the outer layer temperature (curve *2*) due to the conductive component (curve *4*) from the inner layers, and the calculation algorithm is as follows.

The temperature of the ith layer of glass at time $\tau + \Delta\tau$ is equal to

$$T(x_i, \tau + \Delta\tau) = T(x_i, \tau) + \frac{\Delta\tau}{c\rho}[q_r(x_i, \tau) + q_c(x_i, \tau)],$$

where $T(x_i, \tau)$ is the temperature at the preceding moment; c is the specific heat; ρ is the glass density; q_r and q_c are the radiant and conduction components of specific heat at the preceding time moment.

The sheet thickness d is divided into $2n$ layers. Subjected to the condition of a symmetrical temperature distribution with respect to the central section of the plate, the coordinate of the ith layer (except for the surface layer) is equal to

$$x_i = \frac{d}{4n}(2i - 1),$$

and it is sufficient to set $n = 5$.

The conductive component of any layer except for the first one amounts to

$$q_c(x_i, \tau) = \lambda^* \frac{T(x_{i-1},\tau) - 2T(x_i,\tau) + T(x_{i+1},\tau)}{(0.1d)^2},$$

and for the first layer

$$q_c(x_1, \tau) = \lambda^* \frac{2T_s(x_0,\tau) - 3T(x_1,\tau) + T(x_2,\tau)}{(0.1d)^2},$$

where λ^* is the effective thermal conductivity of glass.

The glass surface temperature can be calculated in two stages:

in the first approximation

$$T'_s(x_0, \tau + \Delta\tau) = 1.875T(x_1, \tau) + 0.375T(x_3, \tau) - 1.25T(x_2, \tau),$$

and finally, taking into account surface effects:

$$T_s(x_0, \tau + \Delta\tau) = \frac{AT(x_1,\tau) + \alpha_a T_a - \varepsilon_s[E(T'_s) - 0.7E(T_a)]}{\alpha_a + A},$$

where α_a is the convective heat transfer; ε_s is the reduced degree of blackness of the cooling surfaces; $A = 2\lambda^*/(0.1d)$.

The components $E(T'_s)$ and $E(T_a)$ both represent integral radiation of the article at the surface temperature and at the ambient air temperature, respectively. They are determined from the Stefan – Boltzmann formula [6]:

$$E(T) = 0.37413 \times 10^9 \sum_{\lambda=0}^{\infty} \frac{\Delta\lambda}{\lambda^5\left[\exp\left(\frac{14{,}410}{\lambda T}\right) - 1\right]},$$

where λ is the wavelength.

Further calculations are performed on the basis of the points with coordinates

$$x'_i = \frac{d}{2n}(n - i)$$

with simultaneous conversion to temperature values in °C:

for layers ($i = 1 \ldots n - 1$)

$$t(x'_i, \tau_j) = \frac{T(x_{n-i}, \tau_j) + T(x_{n-i+1}, \tau_j)}{2} - 273.15;$$

for the boundary layers ($i = 0, n$)

$$t(x'_i, \tau_j) = t(x_{n-i}, \tau_j) - 273.15.$$

Next, the real viscosity η of glass is determined using the Tamman – Fulcher and the Arrhenius formulas:

$$\eta(x_i, \tau_j) = \exp\left(A + \frac{B}{T(x_i, \tau_j) - C}\right) \text{ at } 9 \le \log\eta \le 13;$$

$$\eta(x_i, \tau_j) = 10^{A' + \frac{B'}{T(x_i, \tau_j)}} \text{ at } 9 > \log\eta > 13,$$

where A, B, C, A', and B' are constants depending on the glass composition.

Subsequent calculation of temporary and residual stresses corresponds to the procedure described in [1].

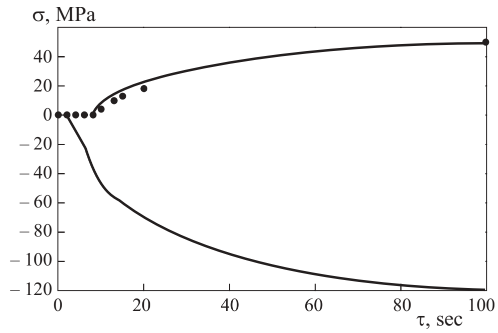

Fig. 3. Temporary stresses in sheet glass during hardening.

Based on the developed complex algorithm, a program was developed and a reference calculation was performed based on experimental data of R. Gardon [5] with the initial conditions; $t(0) = 648°C$, $\alpha = 222.6\ W/(m^2 \cdot K)$, and $d = 6.1$ mm. The correlation results are shown in Fig. 3. The dots indicate experimental data and the lines indicate temporary stresses calculated using the proposed algorithm.

The mean deviation of estimated results from the experimental data amounted to 9.68%.

Based on the considered method, CTT regimes were developed and sheet glass was hardened in accordance with these regimes. The resulting glass has high mechanical strength and is susceptible to mechanical treatment.

Thus, using the Fridkin and Gardon – Narayanaswami algorithms makes it possible to describe conditions of glass hardening with a sufficient accuracy and provides enough reason to calculate nonlinear glass treatment regimes, which makes it possible to predict new consumer properties in sheet glass.

REFERENCES

1. A. I. Shutov, P. V. Popov, and A. A. Chistaykov, “Formation of preset consumer properties in sheet glass,” *Izv. Vuzov, Ser. Stroit.*, No. 10, 101 – 106 (1996).
2. A. I. Shutov, I. A. Novikov, and A. A. Chistyakov, “Cooling capacity of contemporary hardening diffusers,” *Steklo Keram.*, No. 2, 10 – 11 (2000).
3. M. A. Mikheev and I. M. Mikheeva, *Principles of Heat Transfer* [in Russian], Énergiya, Moscow (1997).
4. R. Z. Fridkin and O. V. Mazurin, “A calculation algorithm taking into account radiation heat transfer of the temperature field in a glass plate in heating or in cooling,” *Fiz. Khim. Stekla*, **5**(7), 733 – 736 (1979).
5. R. Gardon, “Thermal tempering of glass,” *Glass: Sci. Technol.*, **5**(10), 145 – 216 (1980).
6. D. B. Zvorykin and Yu. I. Prokhorov, *Use of Radiant Infrared Heating in Electronics* [in Russian], Énergiya, Moscow (1980).